32.5 A 1V 600µW 2.1GHz Quadrature VCO Using BAW Resonators

Shailesh Rai, Brian Otis

University of Washington, Seattle, WA

Digital RF transceiver architectures increasingly require quadrature (I/Q) local oscillator sinusoid generation, where the phase-noise and power consumption of the quadrature voltage controlled oscillator (QVCO) have a significant impact on the system performance. The relevance of VCO power consumption becomes even more urgent due to the demand for implementations of ultra-low power short-range wireless transceivers. This work presents the first bulk-acoustic wave (BAW) resonator-tuned QVCO and introduces a new oscillator coupling mechanism for quadrature signal generation, which is demonstrated on both a BAW- and an integrated LC-tuned QVCO. The design focus is optimization for ultra-low power consumption. Oscillators using high quality factor (Q) BAW resonators have been demonstrated to provide excellent phase noise, supply pushing, and power consumption performance [1]. This work demonstrates a 600µW BAW-based QVCO, providing a figure-of-merit (FOM) significantly greater than the current state-of-the-art. An identical QVCO using an integrated LC-tank with 600µW power consumption is presented for direct comparison with the BAW-tuned QVCO.

Quadrature signal generation is often achieved through anti-phase coupling of two identical differential LC oscillators, using additional coupling transistors in series or in parallel with cross-coupled negative-g_m transistors [2]. A new coupling technique is developed based on time-varying source degeneration of the oscillator switching transistors, providing control over I/Q quadrature accuracy with low phase noise and reduced voltage headroom requirements. The use of matched high Q BAW resonators in the QVCO improves the tradeoff between oscillator power consumption and phase-noise.

The schematic of the oscillator core is shown in Fig. 32.5.1. BAW resonators can be modeled using the modified Butterworth-Van Dyke model (MBVD). C_0 represents the parallel plate capacitance of the BAW resonator. The resonant frequency of BAW resonator is modeled by L_x and C_x, with R_x and R_0 representing resonator losses. The series and parallel loading effect of the CMOS circuitry on the BAW resonator is represented by Z_s and Z_p, respectively. To allow low current operation, the oscillator is designed to operate at the high impedance parallel resonance of the BAW resonator. Unfortunately, the resonator also presents a high impedance capacitive load at low frequencies. Therefore, to avoid low frequency instability, separate current sources for each transistor in the cross-coupled pair are decoupled through a capacitor to provide a high-pass negative resistance [3]. A high value of decoupling capacitance degrades low frequency stability while a low value reduces the oscillator loop gain, mandating careful optimization of the decoupling capacitor. The use of BAW resonators in place of an LC-tank necessitates a common-mode feedback circuit, which was implemented with resistive common-mode sensing and a single-stage operational transconductance amplifier (OTA).

Figure 32.5.2 shows the BAW QVCO architecture with two differential oscillator cores coupled in anti-phase for quadrature signal generation. It is important to minimize the voltage headroom and parasitics added by the quadrature coupling transistors for low power QVCO operation. Differential triode-region switching transistors can be placed in series with the source decoupling capacitor (Cs). These transistors, driven by the opposing oscillator core, degenerate the cross-coupled pair, effectively modulating their negative transconductance. Compared to conventional QVCO coupling methods, this coupling mechanism consumes no voltage headroom enabling operation at low power supplies, while the overdrive voltage of the coupling transistors provides an extra degree of freedom for controlling quadrature accuracy. The phase error between I/Q signals can be regulated by varying the coupling transistor overdrive voltage. Simulations and measurements have shown that the phase difference between I/Q signals can be controlled over a ±5˚ range from 90˚ by varying the coupling transistor bias voltage. An LC QVCO using an identical structure is placed on the same die for direct comparison, which utilizes two on-chip 7nH inductors with unloaded Q of approximately 10 in place of the BAW resonators. Coarse frequency tuning of the QVCO is achieved using a digitally controllable capacitor bank at each output node.

The QVCOs are implemented in a 0.13µm 8-metal CMOS process. Figure 32.5.3 shows the measured quadrature signals generated with the BAW-based QVCO. The coupling transistor bias is set to minimize I/Q phase error. The measured I/Q phase error for both the BAW- and LC-based QVCOs is less than ±1˚, as limited by the test setup. A comparison of the measured frequency spectrum with 1MHz span and resolution bandwidth of 5kHz for the BAW- and LC- QVCOs, both operating at a 600µW power consumption and 1V power supply, is shown in Fig. 32.5.4. The significantly higher unloaded Q provided by the BAW resonators (approximately 1500) compared to the integrated LC tanks (approximately 10) clearly improves the quality of the frequency spectrum and thus the phase noise. The higher resonator Q, however, greatly reduces the tuning range of the BAW QVCO to 1.5 MHz. The LC QVCO achieves a tuning range of approximately 300MHz. The measured phase noise of both oscillators operating at 600µW, overlaid for comparison, is provided in Fig. 32.5.5. The phase noise for the BAW QVCO is -143.5dBc/Hz at 1MHz offset from the 2.1GHz carrier frequency. The LC QVCO achieves a phase noise of -110.7dBc/Hz at 1MHz offset from the 2.2GHz carrier. Although the design value is 600µW, the BAW QVCO achieves reliable startup at a minimum power consumption of 250µW from a 1V power supply.

The standard FOM for oscillators is given by the following:

$$FOM = 10\log\left[\left(\frac{f_o}{\Delta f}\right)^2 \frac{1}{L(\Delta f)\times P_{diss}\,|_{mW}}\right]$$

The BAW QVCO operating at its nominal 600µW operating point achieves a FOM of 212.1dB, which exceeds previously published QVCO implementations. The FOM of the LC QVCO operating at 600µW at a 1V power supply is 179.7dB, which is comparable to other published LC QVCOs. The performance summary and comparison to other recently published QVCOs is shown in Fig. 32.5.6 [4,5,6]. A micrograph of the fully assembled QVCO chip is shown in Fig. 32.5.7. The CMOS chip is wirebonded to two frequency-matched BAW die manufactured in a different process. The measurement results demonstrate that BAW resonator-tuned quadrature oscillators offer compelling power and noise performance improvements over traditional LC-tuned oscillators.

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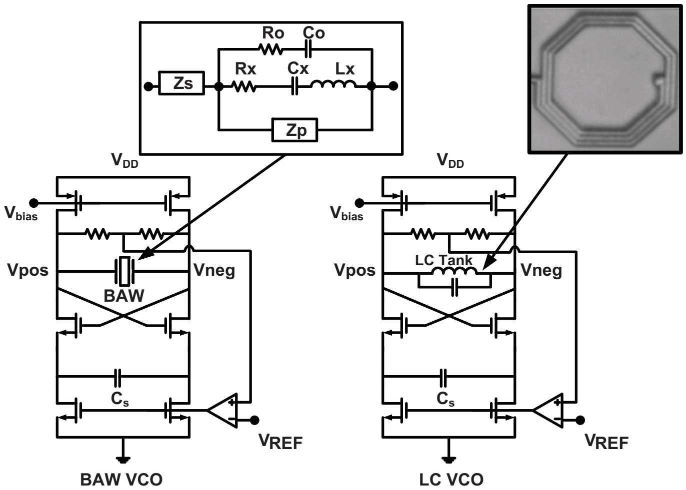

Figure 32.5.1: Schematic of the BAW-and the LC-VCO single core.

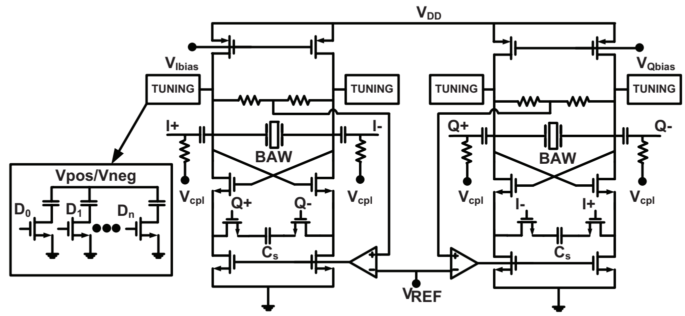

Figure 32.5.2: BAW-tuned quadrature voltage controlled oscillator.

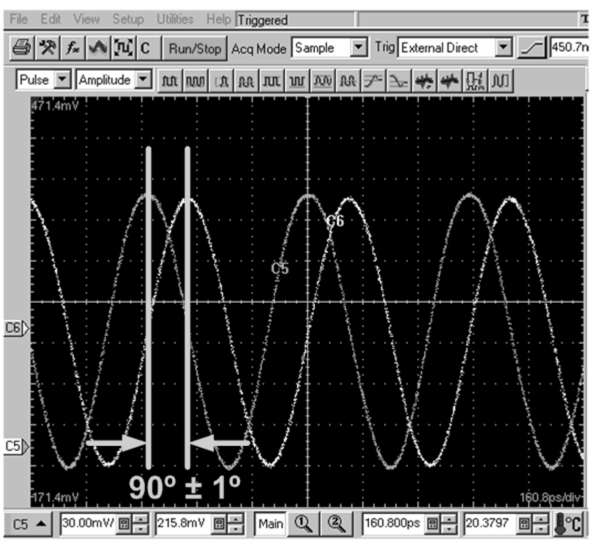

Figure 32.5.3: Measured BAW QVCO quadrature sinusoid output.

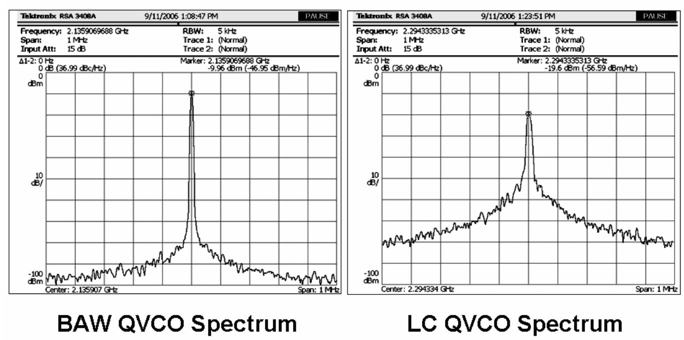

Figure 32.5.4: Measured BAW-and LC-QVCO spectra.

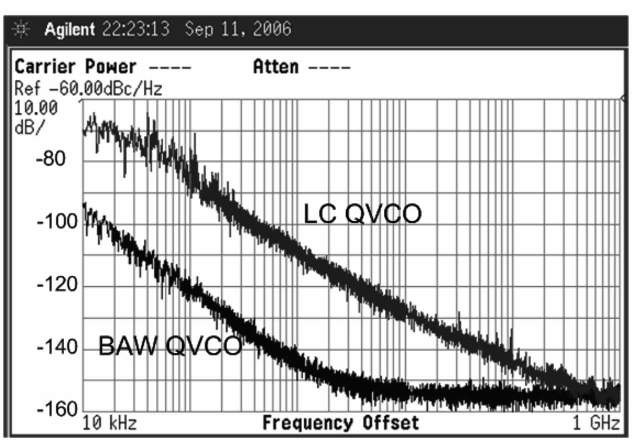

Figure 32.5.5: Measured BAW-and LC-phase noise.

	BAW QVCO	LC QVCO
Technology	0.13µm CMOS	
Center Frequency	2.1GHz	2.2GHz
Tuning Range	< 1%	13.6%
V_{DD}	1V	
Power Consumption	600µW	600µW
Phase Noise @ 1MHz	-143.5dBc/Hz	-110.7dBc/Hz
FOM	212.1dB	179.7dB
Active CMOS area	290µm × 360µm	440µm × 1040µm

	Power Consumption (mW)	Frequency (GHz)	Phase Noise (dBc/Hz) @ 1MHz offset	FOM (dB)	CMOS Technology (µm)
[4]	5	17	-110	187.6	0.18
[5]	27.7	5.1	-132.6	192	0.18
[6]	5.4	1.1	-120	173.5	0.18
This work (BAW)	0.6	2.1	-143.5	212.1	0.13
This work (LC)	0.6	2.2	-110.7	179.7	0.13

Figure 32.5.6: Performance summary and comparison.

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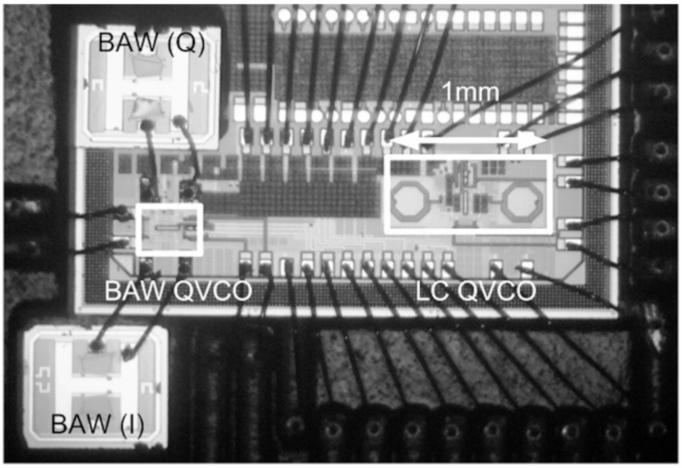

Figure 32.5.7: Chip micrograph of BAW-and LC-QVCO.

